

# Verification of finite element modelled displacements using ShapeArray inclinometers

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**ABSTRACT:** Monitoring and instrumentation are critical for evaluating the stability and safety of tailings storage facilities (TSFs). This study investigates the use of ShapeArray (SAA) inclinometers to validate foundation displacement predictions made by finite element (FE) deformation modelling. Sixteen vertical SAAs were installed in an upstream-constructed platinum TSF, with six of these selected for detailed comparison with FE model results. Real-time SAA measurements were assessed alongside predicted displacement profiles to evaluate the reliability of the model. The field measurements consistently demonstrated significantly lower displacement magnitudes than those predicted by modelling. The findings highlight the importance of integrating high-resolution monitoring data with numerical modelling to refine deformation predictions and establish realistic trigger thresholds for a trigger action response plan. This work contributes to improved early warning systems and enhanced risk management practices in tailings engineering.

**KEYWORDS:** Inclinometers, deformation, monitoring.

## 1 INTRODUCTION

The accurate prediction and monitoring of deformations in tailings storage facilities (TSFs) are critical to safe operational performance. As the industry moves toward more rigorous risk management, particularly in the aftermath of incidents such as the Brumadinho failure, the integration of advanced instrumentation with numerical modelling has become essential.

Finite element (FE) models are widely used to simulate the mechanical behaviour of TSFs under various conditions. While these models provide a powerful tool for predicting deformation, their reliability is highly dependent on validation through high-quality, site-specific field measurements. ShapeArray inclinometers (SAAs), which offer continuous, high-resolution monitoring of ground deformations, present a valuable opportunity for such validation.

This paper presents a case study from a platinum TSF where SAA measurements were compared to foundation displacements predicted by FE modelling. The primary objective was to assess whether field performance aligned with modelled predictions and to evaluate how real-time monitoring can inform trigger action response plans (TARPs) and enhance TSF safety management strategies.

## 2 SHAPEARRAY INCLINOMETERS

SAAs represent a significant advancement in geotechnical instrumentation, offering continuous, automated monitoring of subsurface deformation with high spatial and temporal resolution. Unlike conventional manual inclinometers, which require periodic readings using portable probes, SAAs deliver near real-time, three-dimensional displacement data, thereby enhancing the resolution and reliability of performance monitoring in geotechnical systems (Dixon et al. 2020; Smith, 2019).

SAAs comprise a chain of microelectromechanical system (MEMS) sensors, including accelerometers and gyroscopes, embedded within a flexible casing. Each 0.5 m segment measures tilt, and cumulative tilt is used to derive full-profile displacement vectors (Measurand, 2021). These arrays are typically installed in boreholes or trenches, and data acquisition is achieved remotely via data loggers and telemetry systems. This configuration allows for continuous deformation monitoring over time and supports high-frequency data capture, often on an hourly or sub-hourly basis. The system also reduces the need for manual site visits, enhancing safety in potentially hazardous or remote environments.

Compared to traditional manual inclinometers, SAAs offer superior data density and early detection capabilities, making them ideal for integration into comprehensive monitoring strategies. Their compatibility with other geotechnical instruments, such as piezometers or seismic sensors, enables a holistic understanding of site behaviour (Li and Zhang, 2011). Additionally, the availability of real-time data supports timely decision-making and structured responses through TARPs.

However, the use of SAAs is not without limitations. The initial capital cost is generally higher than that of conventional systems, and their performance is highly sensitive to the quality of installation. Factors such as poor casing centralisation, inconsistent grout properties, or mechanical damage during installation, especially in deep boreholes or stiff soils, can compromise the quality of the data. Furthermore, the system's reliance on uninterrupted power supply and telemetry infrastructure introduces operational risks, and data interpretation may become complex in layered or heterogeneous ground conditions (Becker et al. 2010; Jefferies & Been, 2015).

Environmental influences such as temperature fluctuations, vibrations, or water ingress can also affect sensor performance. Nonetheless, recent advances in SAA software tools such as Measurand's SAAView and SAACR have improved data reliability through enhanced filtering, noise reduction, and temperature compensation. These platforms can also convert raw SAA data into outputs that mimic traditional inclinometer profiles, enabling easier comparison and integration into established workflows. The addition of automated visualisation tools and alert systems has further enhanced the value of SAAs in proactive TSF safety monitoring (Measurand, 2021; ICOLD, 2022).

Despite the noted challenges, SAAs continue to prove instrumental in strengthening risk management practices in tailings engineering by offering real-time insights into ground behaviour that support timely interventions and model validation.

## 3 SITE DESCRIPTION AND INSTRUMENTATION

The TSF being monitored is a hillside, upstream-constructed facility used for the deposition of platinum tailings. The tailings material consists of highly variable composition predominantly silty fine sand, silty sand, silt, and occasionally clayey silt. These tailings become more compact with depth and overlie a foundation sequence comprising alluvium, residual norite, and weathered norite bedrock.

In 2023, sixteen vertical SAAs were installed across the TSF to capture deformation and to support ongoing performance monitoring. The SAAs were strategically positioned within the embankment, foundation, and basin body. Each array consists of sensors at 0.5 m spacing, capturing hourly displacement data via remote loggers and telemetry.

This paper focuses specifically on six of the installed SAAs, which are located across three of the critical TSF sections (Figures 1 to 3). The sensors used for this research in the foundation materials are indicated by the circular markers on each section.

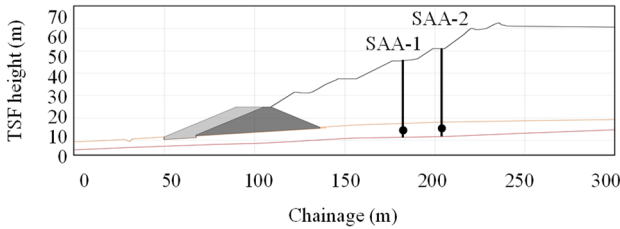


Figure 1. SAA installations along Section 1.

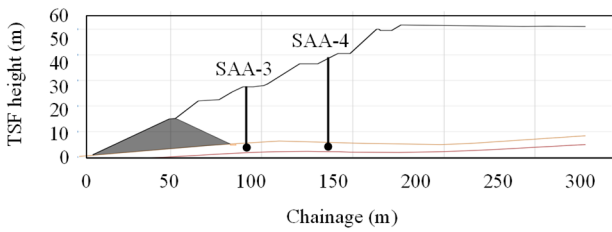


Figure 2. SAA installations along Section 2.

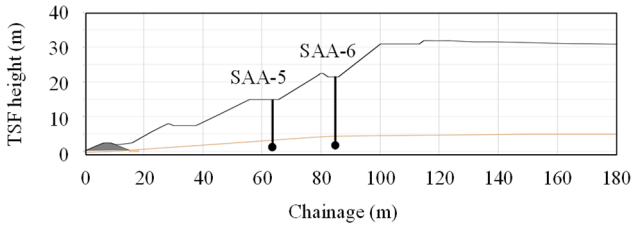


Figure 3. SAA installations along Section 3.

#### 4 MEASURED DISPLACEMENTS

Cumulative displacements were recorded over a 12-month period, as shown in Figures 4 to 9. These plots illustrate the measured displacement in the two principal lateral directions:

- X-direction: movement in the downstream direction (blue trace). Positive values represent downstream displacement, negative values represent upstream (inward) displacement.
- Y-direction: movement parallel to the TSF toe (red trace). Positive values represent displacement toward the eastern embankment sector, negative values represent displacement toward the western embankment sector.

For the purpose of this study, the displacements reported correspond specifically to the foundation measurement nodes that align with the FE model comparison locations. These nodes are indicated by the black circular markers in Figures 1 to 3. Therefore, each displacement trace represents the cumulative movement recorded at the identified single depth point within the SAA that intersects the deforming foundation layer.

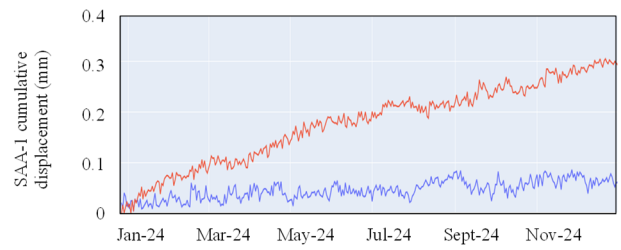


Figure 4. SAA-1 measured cumulative displacement.



Figure 5. SAA-2 measured cumulative displacement.

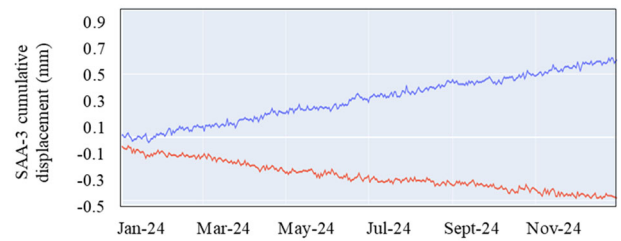


Figure 6. SAA-3 measured cumulative displacement.

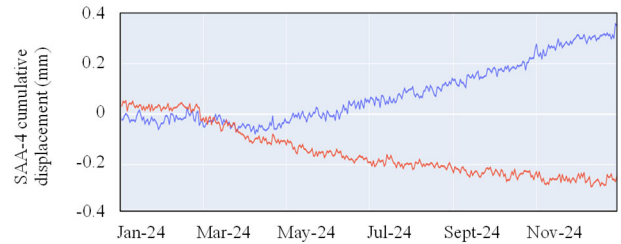


Figure 7. SAA-4 measured cumulative displacement.

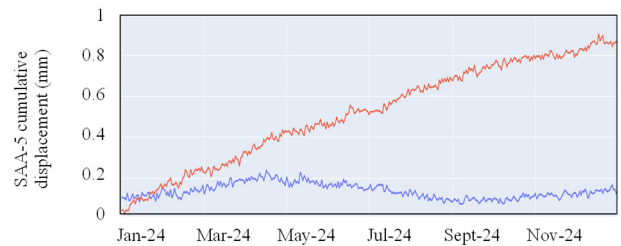


Figure 8. SAA-5 measured cumulative displacement.

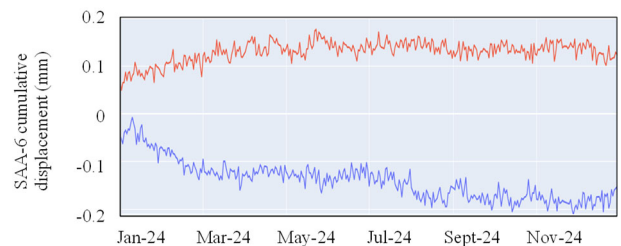


Figure 9. SAA-6 measured cumulative displacement.

## 5 DEFORMATION MODELLING

A numerical deformation model was developed using PLAXIS 2D, an FE software widely used for deformation and stability analysis of geotechnical structures. The model incorporated a staged-construction approach, simulating the progressive deposition of tailings over time. This allowed for the prediction of displacements associated with sequential lifts, enabling a realistic representation of operational conditions.

Outputs from the deformation model were provided for this paper. These outputs include displacement profiles developed across discrete construction stages to reflect ongoing tailings deposition. Figures 10 to 12 present the displacement profiles for the foundation material at each of the six SAAs.

By comparing these results with the field-measured SAA data, an assessment of model accuracy was possible, providing valuable input for future model calibration. The inclusion of such modelling within the broader TSF monitoring strategy supports proactive management by offering predictive insights that complement real-time observations.

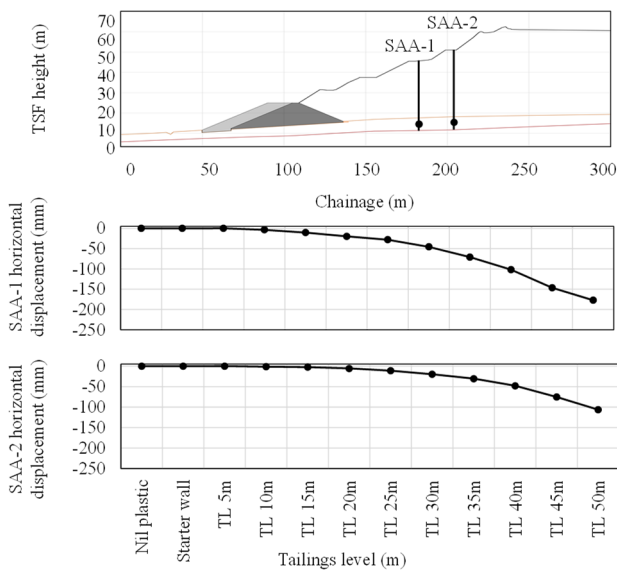


Figure 10. SAA-1 and SAA-2 modelled displacement profiles.

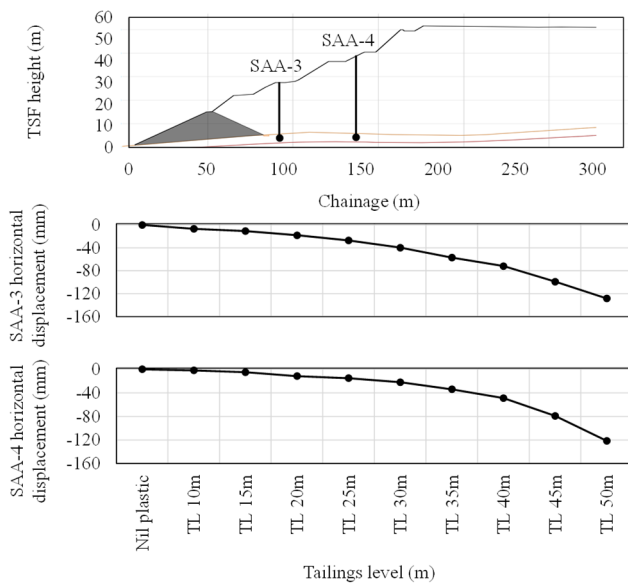


Figure 11. SAA-3 and SAA-4 modelled displacement profiles.

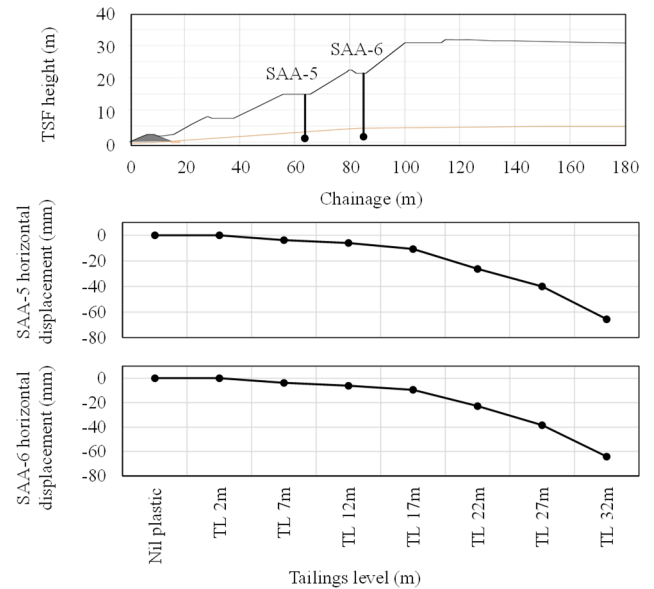


Figure 12. SAA-5 and SAA-6 modelled displacement profiles.

## 6 RESULTS

### 6.1 Observed displacement behaviour

During the 12-month monitoring period, the SAAs recorded relatively low rates of lateral displacement across all six locations. The resultant lateral displacement was calculated from the two orthogonal displacement components presented in Figures 4 to 9. The measured average displacement rates ranged from 0.2 mm/year at SAA-6 to 0.9 mm/year at SAA-5. When normalised per vertical metre of tailings lift, the corresponding displacements ranged from 0.1 mm/m to 0.7 mm/m. These values indicate that minimal lateral deformation occurred within the instrumented zones, suggesting stable conditions and no apparent signs of progressive failure or instability during the observation period.

The spatial distribution of the measured displacements shows some variability between instruments, likely due to differences in foundation conditions, drainage, and tailings deposition history. Nevertheless, all observed displacements remained within the expected operational range and well below predefined trigger levels specified in the site's TARP.

Modern SAA systems have a displacement repeatability of approximately  $\pm 0.5$  mm over the full instrument length and node-level resolution on the order of  $\pm 0.2$  mm (Measurand, 2021). Although the measured displacements in this study are small, they exceed the short-term noise threshold when evaluated cumulatively over the 12-month period.

A summary of the measured and predicted displacement data for each SAA is provided in the Table 1.

Table 1. Comparison between measured and modelled displacement.

SAA	Measured values		Modelled values	
	Average $\Delta r$ (mm/year)	Normalised average $\Delta r$ (mm/1m lift)	Average $\Delta r$ (mm/year)	Normalised average $\Delta r$ (mm/1m lift)
1	0.3	0.2	7.7	5.9
2	0.7	0.5	7.7	5.9
3	0.8	0.6	7.3	5.6
4	0.4	0.3	10.6	8.2
5	0.9	0.7	5.1	3.9
6	0.2	0.1	5.1	4.0

## 6.2 Comparison with numerical modelling outputs

Across all locations, the predicted displacement rates were significantly higher than those observed in the field. Modelled displacements ranged from 5.1 mm/year to 10.6 mm/year, with normalised values between 3.9 mm/m and 8.2 mm/m. In contrast, field measurements were an order of magnitude lower. This divergence is most notable at SAA-3, where a measured displacement rate of 0.8 mm/year contrasts sharply with a predicted rate of 7.3 mm/year. Similarly, SAA-1 recorded only 0.3 mm/year in the field, compared to 7.7 mm/year from the model.

## 6.3 Interpretation and discussion

Several factors may account for the observed discrepancies between the measured and predicted displacement rates. One likely explanation lies in conservative assumptions embedded in the numerical model. The model may have overestimated deformations due to simplifications in representing tailings behaviour during staged deposition and consolidation.

Additionally, the actual field performance may have benefitted from site-specific conditions not captured in the modelling framework. For example, effective drainage, operational compaction, or other engineering controls could have enhanced stability and limited lateral movement. It is also possible that the model's constitutive laws, especially if incorporating strain-softening behaviour, do not fully reflect the in-situ mechanical response of the tailings and foundation materials under the current loading regime.

The field monitoring system is actively supported by a TARP that defines specific thresholds for lateral movement and triggers structured responses. Importantly, all measured displacement values remained well below the TARP's alert thresholds during the monitoring period. No exceedances or alerts were recorded. The TARP incorporates real-time SAA data and serves as a dynamic risk management tool that allows for rapid investigation and corrective action should abnormal trends emerge.

To further interpret the measured deformation, a simplified estimate of strain rate can be calculated by dividing the observed displacement by the thickness of the deforming material. Using the maximum measured annual displacement of 0.9 mm (at SAA-5), the corresponding strain rate is approximately 0.03% per year. This low strain rate indicates very stable conditions, with minimal shear deformation occurring in the foundation. This supports the field observation that no progressive strain accumulation or structural instability was present during the monitoring period.

The consistent gap between modelled and measured displacements highlights the critical role of field instrumentation not only for early warning but also for the iterative calibration of predictive models. In this context, the SAA data serve as a feedback mechanism that enhances model realism and informs more accurate and less conservative design and operational decisions.

## 7 CONCLUSIONS

SAAAs have become an essential component of modern geotechnical monitoring strategies, particularly in the wake of high-profile TSF failures such as the Brumadinho disaster. Their ability to deliver high-resolution, real-time displacement data provides engineers and operators with a powerful tool for early detection of ground movement and for proactive risk mitigation. In the context of TSFs, where deformation behaviour is complex and highly variable, SAAAs offer valuable insights that traditional monitoring methods may not capture.

The findings from this study demonstrate the critical role that SAAAs can play in validating and calibrating numerical deformation models. By comparing real-time field data from six vertical SAAAs with displacement predictions generated by an FE model, it was possible to assess the accuracy and conservatism embedded in the modelling framework. In all six cases, the measured lateral displacements were significantly lower than those predicted, with differences often exceeding an order of magnitude. These discrepancies underscore the importance of integrating field-based instrumentation data into modelling workflows, particularly for complex, layered geotechnical systems like those encountered in TSFs.

Several potential explanations were identified for the observed mismatch between modelled and measured displacements. These include conservative material parameters, simplified assumptions regarding tailings behaviour, and unmodelled site-specific factors such as enhanced drainage or operational controls. Regardless of the source, the presence of such discrepancies reinforces the need for continuous model refinement based on field performance, particularly when models are used to define thresholds in TARPs.

The implementation of a structured TARP at the study site, incorporating real-time SAA data, has proven effective in providing early warning capability and guiding operational decisions. Throughout the monitoring period, no displacement thresholds were exceeded, and the facility remained in a stable condition, as evidenced by the low displacement rates recorded across all instruments.

In conclusion, the integration of high-resolution SAA data with numerical modelling tools not only enhances the reliability of deformation predictions but also contributes to more effective, evidence-based risk management strategies. As the mining industry continues to adopt more stringent safety standards, the use of such integrated approaches will be increasingly important for ensuring the long-term stability and sustainability of TSFs.

Future work should focus on further refining model parameters using site-specific monitoring data, investigating the role of operational practices in displacement trends, and expanding the monitoring network to improve spatial coverage. Such efforts will contribute to the development of more accurate, adaptive, and resilient geotechnical monitoring systems.

This study contributes to the growing body of evidence supporting the integration of high-resolution instrumentation with modelling tools to improve the safety and performance assessment of TSFs.

## 8 REFERENCES

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